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PAPER MILL COGENERATION POWER PLANT ASSISTED BY LINEAR FRESNEL SOLAR COLLECTORS

Authors: Eduardo Burin[1], Pedro Lo Giudice[2], Edson Bazzo[3]

1. University of Parana (UFPR), Department of Engineering and Exact Sciences (DEE), Brazil
2. TGM Turbines, Brazil.
3. University of Santa Catarina (UFSC), Lab. of Combustion and Thermal Systems Engineering (LabCET). Brazil

ABSTRACT

The objective of this work is to evaluate the integration of a linear Fresnel field in a feedwater heating scheme with a paper mill cogeneration plant to provide additional electricity generation. The plant in question is located in Mato Grosso do Sul state and is equipped with a cogeneration cycle that uses a regenerative feedwater heating system. The steam generator has a 600 t/h capacity and provides steam at 91 bar / 490 °C. Main steam is expanded in a backpressure and a condensing steam turbine. Solar integration is evaluated to displace the high-pressure steam extraction (34 bar) by preheating feedwater at 120 bar from 150 to 200°C at design point. The otherwise extracted steam is expanded in the condensing turbine providing power boost. Simulations were performed using EES software for a typical meteorological year. 11,955 MWh additional electricity was observed after hybridization (+1.7% when compared to the base case operation) at LCOE ranging from 160 to 215 US$/MWh depending on solar field investment. The solar-to-electricity efficiency was equal to 13%. This work demonstrated the gains due to integration of solar concentrators with a paper cogeneration plant, representing an opportunity to increase the capacity of these units to export additional power to the grid.

Keywords: Biomass; paper mill; cogeneration; solar energy; linear Fresnel.

INTRODUCTION

Concentrated Solar Power (CSP) integration into conventional Rankine power plants allows reducing solar energy implementation costs. Furthermore, there's the possibility of base load power supply without the cost intensive thermal storage systems, as the solar energy can be used to displace fuel consumption. In the case of power boost operation mode, the solar energy can also be used to improve electricity production during sunny hours.

A promising integration layout consists of solar feedwater heating. This concept is based on substituting turbine bleed-off steam extractions in regenerative cycles by providing feedwater preheating with solar energy. In this context, [1] has shown that integrating solar energy at the higher temperature feedwater heaters is more efficient than at the low-pressure side ones. This is because of the higher grade thermal input related to higher temperature energy sources.

In Brazil, the installed capacity of biomass power plants reached 14 GW. Of this amount, 2.3 GW is produced in paper mills by cogeneration power plants fueled with black liquor. Also, electricity exporting to the grid by pulp and paper industries has recently improved by burning additional biomass. Considering the sector's importance to Brazil's electricity matrix and considering the relevant DNI incidence in Brazil, the objective of this work is to evaluate the integration of a linear Fresnel solar field in a feedwater heating scheme with a typical state-of-the-art paper mill cogeneration plant located in Mato Grosso do Sul, Brazil. Linear Fresnel technology has the advantage of avoiding the use of an intermediary heat transfer fluid (HTF) and, as a consequence, HTF-water heat exchangers once steam is generated (or water is preheated) directly in the receivers. This work extends a concept previously presented related to the hybridization of sugarcane bagasse power plants, as presented by the authors in previous works [2,3].

METHODS

Power plant description

In this work, a paper mill cogeneration power plant fueled by biomass (Eucalyptus wood chips) was simulated to evaluate its integration with a linear Fresnel solar field in a feedwater heating scheme. The cogeneration plant is integrated into a paper factory that uses saturated steam at 5 bar and 12 bar to supply the heat demand.

Corresponding author: Eduardo Burin. Palotina 85950-000 Brazil. Fone: +55-44-3211-1350. e-mail: eduardo.burin@ufpr.br

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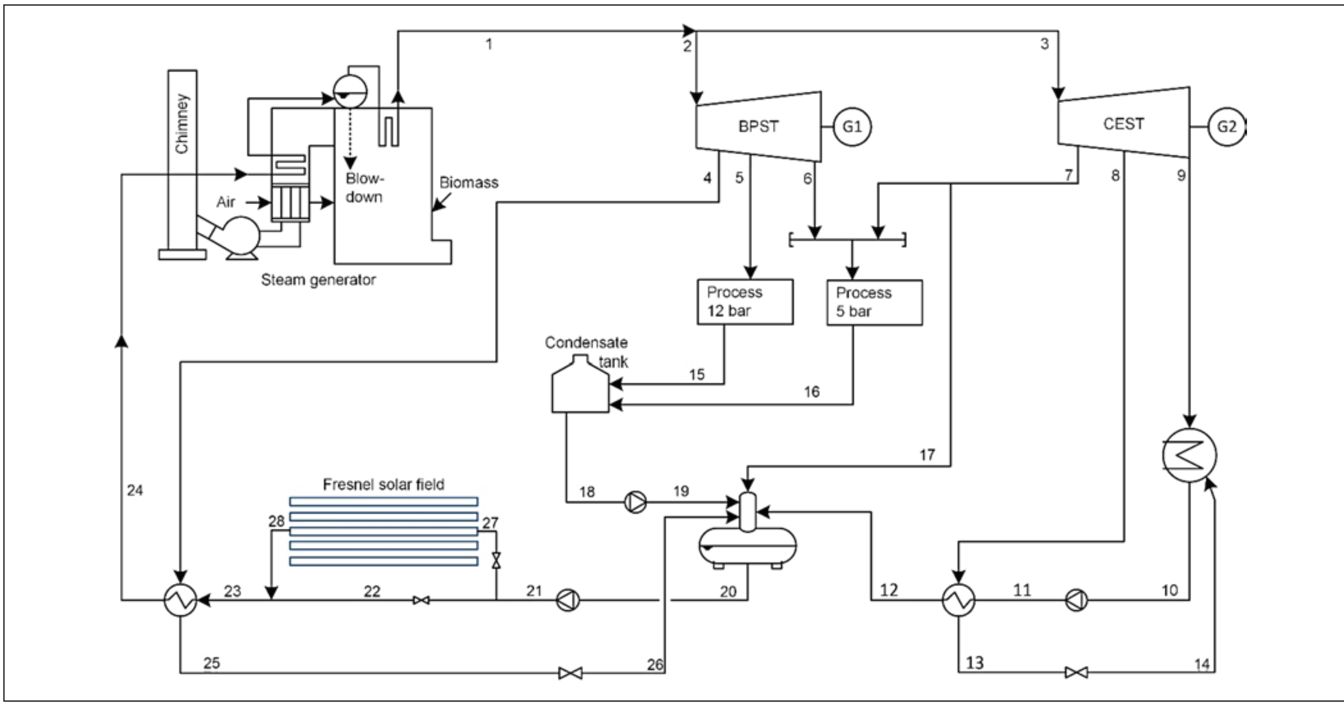

Figure 1. Cogeneration cycle layout and solar integration used to boost power output.

The solar aided plant layout is presented in Figure 1. The steam cycle is equipped with one 600 t/h capacity steam generator that produces superheated steam at 490°C / 91 bar. The back-pressure turbine has one steam extraction at 34 bar (point 4) to feed the high pressure feedwater heater (200ºC feedwater final temperature) and two extractions at 12 bar (point 5) and 5 bar (point 6) to feed the process heat load. The remaining steam is expanded in a condensing steam turbine. This turbine presents one extraction at 5 bar to complement the process heat demand and to feed the deaerator, one extraction at 0.9 bar to feed the low pressure feedwater heater and the remaining steam is expanded until point 9 to the condenser.

The solar field is evaluated in this work to provide feedwater heating at point 23. The high-pressure feedwater heater load is then minimized and the otherwise bleed-off steam extraction is expanded in the condensing turbine. As the superheated steam flow at point one is kept constant, the power output is increased during sunny hours reaching the power boost operation at sunny hours.

Thermodynamic modeling

The thermodynamic performance of steam cycle was estimated by a component-wise modeling based on first law and mass conservation equations followed by a simulation using the computer software Engineering Equation Solver (EES). The adopted assumptions for steam cycle modeling are presented below:

- Isentropic efficiency of steam turbines was set as 85%;
- The efficiency of electricity generators connected to back-pressure and condensing turbines was set equal to 96%;
- Thermal efficiency of steam generators based on fuel's Lower Heating Value (LHV) was set equal to 85%;
- The biomass Lower Heating Value (LHV) at 45% moisture was considered equal to 2,580 kcal/kg.

The Industrial Solar LF11 [4] linear Fresnel solar collector assembly was considered in this work. The heat absorbed by water in receivers, $\dot{Q}_{sf}$ [W] was simulated according to the steady-state model represented by Equation (1),

$$\dot{Q}_{sf} = A_{sf}\,(I_{bn}\eta_{opt} - \dot{Q}''_{loss}) \quad (1)$$

where I_{bn} [W/m²] is the direct normal radiation, η_{opt} is the solar field optical efficiency, which is calculated according to Equation (2) and $\dot{Q}''_{loss}$ is the heat loss to ambient [W/m²], which is calculated according to the empirical correlation represented by Equation (3).

$$\eta_o = \eta_{opt,0}\, K_L\, K_T \quad (2)$$

$$\dot{Q}''_{loss} = u\,\Delta T^2 \quad (3)$$

The simulation of LF11 assemblies was performed using the software Matlab. A typical meteorological year data set was considered for the city of Campo Grande, Mato Grosso do Sul (-54.667º, -20.467º) obtained from software Meteonorm. The design point radiation, $I_{bn,ref}$ [W/m²], adopted to size the solar field was set as 950 W/m² at solar noon. The solar field was sized to displace

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the back pressure turbine high pressure steam extraction at the design point. In order to achieve this condition, it was proposed the installation of 58,840 m² aperture area LF11 concentrators on a land area of 8.9 ha. The layout of solar field consisted of 170 loops of 16 SCAs each. The integration was simulated considering one-hour time steps.

Annual performance indexes

Some annual performance indexes are presented below. The thermal efficiency of solar field along the year was calculated by Equation (4), where i is the time step of simulation – hour of the year [1:8760].

$$\eta_{sf} = 100 \sum_{i=1}^{8760} \frac{\dot{Q}_{sf}(i)}{A_{sf}\, I_{bn}(i)} \tag{4}$$

The additional energy generated due to solar power boosting, AE [MWh], was quantified by Equation (5),

$$AE = \sum_{i=1}^{8760} \dot{W}_{net,h} - \dot{W}_{net,b} \tag{5}$$

where $\dot{W}_{net,b}(i)$ and $\dot{W}_{net,h}(i)$ are the net power output at time ii for base and hybrid cases in MW.

Taking AE into consideration, the annual solar irradiation to electricity efficiency of the hybrid cycle, η_{se}, was calculated by Equation (6)

$$\eta_{se} = 100\times \frac{AE}{\sum_{i=1}^{8760} A_{sf}\, I_{bn}(i)} \tag{6}$$

The Levelized Cost of Electricity (LCOE) [US$/MWh] was calculated according to the methodology proposed in [5]. The LCOE was calculated for the additional power generated due to hybridization, AE [MWh],

$$LCOE = \frac{\sum_{t=0}^{lt}(CC + LC + O\&M)\cdot(1+r)^{-t}}{\sum_{t=0}^{tf} AE \cdot (1+r)^{-t}} \tag{7}$$

where CC, LC and O&M [US$] are the capital, land and annual operation and maintenance costs. The parameter r represents the interest rate and it is the lifetime of plant. The cost parameters used for economic analysis are presented in Table 1.

RESULTS AND DISCUSSION

The main results related to base case power plant simulation are presented in Table 2. The presented net electricity production consists of the remaining after discounting parasitic consumption of pumps, steam generator, cooling tower and other equipment. As stated before, the paper mill also requires electricity. Thus, the exported electricity consists of the remaining that can be inserted in the national grid after discounting local consumption.

Table 2. Annual performance of base case power plant

Parameter	Hourly basis (average)		Annual operation	
Burned biomass	180.0	t/h	1,576,800	t
Back-pressure turbine gross output	61.0	MW	534,360	MWh
Condensing turbine gross output	36.3	MW	320,616	MWh
Net electricity production	79.6	MW	697,296	MWh
Process heat consumption	316.6	MW	2,773,416	MWh

The solar field was designed to totally displace the turbine high-pressure steam extraction (Figure 1 - point four) at solar field full load operation. As seen in Table 3, the solar field available heat was equal to 34.4 MW. This corresponded to preheating 611 t/h of water at point 21 from 151 to 197°C. For the reference DNI of 950 W/m², the design point solar field thermal efficiency was equal to 57%. The additional amount of produced electricity at the condensing turbine due to steam extraction displacement was equal to 11.6 MW at design point condition, obtaining solar-to-electricity efficiency of 19%.

Table 3. Design point results of hybrid plant.

Point	Temperature [°C]	Pressure [bar]	Enthalpy [kJ/kg]	Mass flow [t/h]
27	150.7	120.0	642.6	611.3
28	197.4	120.0	845.2	611.3
Asf=59,840 m²; land area = 8.9 ha; Ibn,ref=950 W/m²;Qav,ref=34.4 MW; AE=11.6 MW; Eta_sf-ref=57 %; Eta_se=19 %				

After the design point analysis, an annual simulation was performed for a typical meteorological year. One example day of operation is presented in Figure 2. The DNI is represented by the blue color. The available heat delivered by solar field per square meter of aperture area is represented by the orange color. The

Table 1. Parameters used for economic analysis.

Parameter	Unit	Adopted assumption
Site improvements	US$/ha	250,000
Solar field investment [6]	US$/m²	230 – 320
Land investment	US$/ha	20,000
EPC and contingencies	US$	20 % of DC
Material replacement	USS$/year	1 % of DC
Interest rate, r	-	8 %
Life time of plant, lt	Years	25

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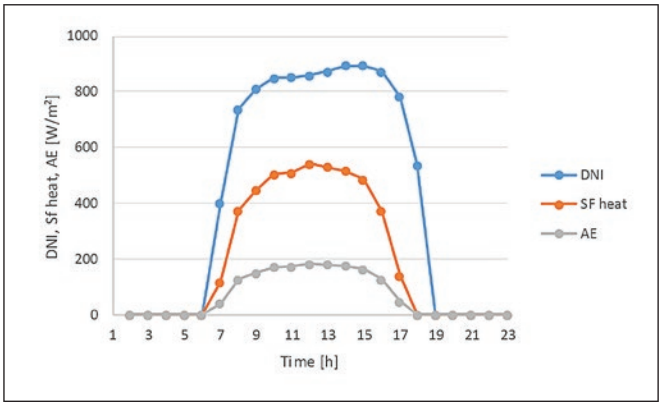

Figure 2. Example day of operation of hybrid plant

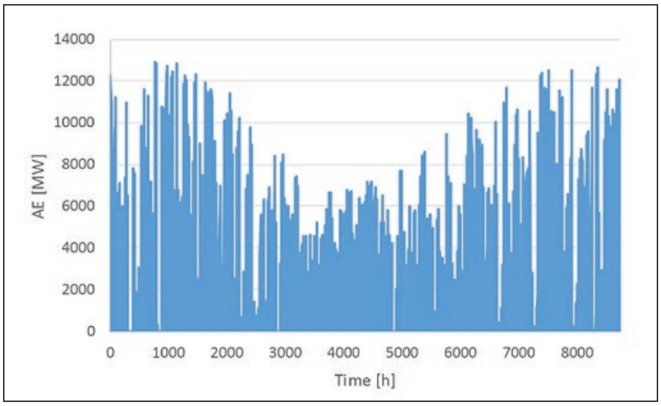

Figure 3. AE output profile along a typical year

Table 4. Annual performance data of hybrid plant

Performance index	Unit	Hybrid case
Accumulated DNI	kWh/m^2year	1,517
Additional electricity output, AE	MWh	11,955 (+ 1.7% to the base case)
Solar field thermal efficiency, η_{sf}	%	39.0
Solar to electricity efficiency, η_{se}	%	13.0
Levelized Cost of Electricity, LCOE	US$/MWh	160 to 215

difference between DNI and the heat delivered by solar field is due to the thermal efficiency of solar field. Lastly, the gray color curve represents the instantaneously additional electricity output of the condensing turbine (transformed to W/m2 for comparison), due to bleed-off steam displacement by solar energy.

The main results related to the annual simulation of the hybrid plant are presented in Table 4. The local year-round accumulated DNI was equal to 1,517 kWh/m^2year, which is a low value compared to regions where CSP plants are typically installed. The total additional power produced due to solar integration was equal to 11,955 MWh. This corresponded to increasing energy production by 1.7% when compared to the base case. The year-round mean solar field efficiency was equal to 39%, which is a lower value when compared to the reference condition since there are off-design degradation factors. In the case of solar-to-electricity efficiency of hybrid system, the 13.0% result obtained is similar to that obtained under Fresnel CSP plants under operation where efficiency ranges from 9-13% [7]. Lastly, the LCOE result ranged from 160-215 US$/MWh as the capital investment of solar field was ranged from 230-320 US$/m². This can be considered an attractive result despite the reduced local DNI incidence and the main reason for the reduced LCOE results consists of the low-cost Fresnel collector applied to perform de feedwater heating from 151 to 200°C – low temperature requirement.

A visual representation of the hybrid cycle additional power generation along the year is shown in Figure 3. It's possible to observe the lower output of the hybrid system during the winter season, due to higher optical and thermal losses in solar field.

CONCLUSION

The hybrid operation of cogeneration plant assisted by linear Fresnel solar collectors used to preheat feedwater made it possible to increase the electricity output as additional steam was displaced to the condensing turbine. Despite the local low DNI incidence in the selected region, the LCOE ranging from 160-215 US$/MWh was attractive. This result is due to the reduced linear cost of Fresnel system applied to perform feedwater heating – low temperature requirement. As a next step, this work can be replicated to real cogeneration plants operating in Brazil to assess feasibility of the proposed concept. ■

REFERENCES

1. Hou, H. Yang, Y. Hu, E. Song, J. Dong, C. Mao, J. "Evaluation of solar aided biomass power generation systems with parabolic trough field", *Science China Technological Sciences,* vol54, pp1455-61. (2011).
2. Burin, E. Buranello, L. Giudice, P. Vogel, T. Goerner, K. Bazzo, E. "Boosting power output of a sugarcane bagasse cogeneration plant using parabolic trough collectors in a feedwater heating scheme", Applied Energy, vol154, pp232-41. (2015).
3. Burin, E. Vogel, T. Multhaupt S. Thelen, A. Oelkeklaus G. Goerner, K. Bazzo, E. "Thermodynamic and economic evaluation of a solar aided sugarcane bagasse cogeneration power plant". Energy. pp1-13. (2016).
4. Industrial Solar. LF11 technical data. Available at:< http://www.industrial-solar.de/content/en/maerkte/fresnel-collector/>.
5. Projected costs of generating electricity, Tech. rep., International Energy Agency; Nuclear Energy Agency; Organization for Economic Cooperation and Development (2010).
6. Platzer, W. Dinter, F. Cuevas, F. Low-cost Linear Fresnel Collector, Tech. rep., WP6: International Cooperation Activities. Scientific and Technological Alliance for Guaranteeing the European Excellence in Concentrating Solar Thermal Energy (2016).
7. Renewable Energy Technologies - cost analysis series - Concentrated Solar Power, Tech. rep., IRENA (2012).